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Comparative assessment of future motor vehicles under various climate change mitigation scenarios

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ABSTRACT

The aim of comparative assessment of future road transport technologies is to find the cheapest motor vehicles in terms of private and external Greenhouse Gas (GHG) emission costs under various international climate change mitigation scenarios in 2020 and 2050. The comparative assessment of the main road transport technologies ranging from conventional vehicles to hybrid electric vehicles was performed. The main indicators for comparative future motor vehicles assessment are: private costs and life cycle external costs of GHG emissions. The obtained ranking of road transport technologies allows to identify the most perspective future motor vehicles taking into account international climate change mitigation constraints and to promote these road technologies by policy tools. The cheapest road transport technologies in 2020 and 2050 are: the main results presented in this paper were obtained during EU financed Framework 7 project "PLANETS" dealing with probabilistic long-term assessment of new energy technology scenarios.

Contents

1. Introduction

Combating climate change is a top priority for the European Union (EU). Road transport contributes about one-fifth of the EU's total emissions of carbon dioxide (CO_2), the main greenhouse gas (GHG). While emissions from other sectors are generally falling, those from road transport have continued to increase since 1990. Therefore GHG emission reduction from motor vehicles is a major challenge for EU climate change mitigation policy. Modest increases in vehicle efficiency have been offset by increased number of vehicle fleet and total travel.

There are few main approaches for reducing GHG emissions from motor vehicles:

- Improving fuel economy using hybrid electric vehicle (HEV);
- Implementing low carbon fuel such as bioethanol or biodiesel;
- Substitution of the portion of petroleum by electricity used to power vehicle using plug-in hybrid vehicle (PHEV).

The future development and deployment of new road transport technologies in EU highly depends on carbon constraints set by international climate change mitigation regimes. As climate change mitigation is the central environmental policy in EU the long-term assessment of new road transport technologies under various long-run climate change mitigation scenarios is useful for policy makers taking into account just 2 main criteria: private (fuel and motor vehicle) costs and external GHG emission costs. Such assessment

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Table 1
GHG reduction commitments applied in policy scenarios.

Regions	Starting date of commitments	Commitments SC1 in 2050 w.r.t. 2005 (%)	Commitments SC2 in 2050 w.r.t. 2005 (%)
OECD	2015	−80	−90
Energy exporting (EEX)	2025	−50	0
Developing Asia (Dev. Asia)	2025	+25	0
Rest of the world (ROW)	2025	+55	+100
World w.r.t. 2005		−28	−26

would help policy makers to identify the most promising motor vehicles in terms of GHG emission reduction and to develop policy tools to promote them.

The aim of the paper is to find the cheapest motor vehicles in terms of private (fuel and vehicle) and external GHG emission costs under various international climate change mitigation scenarios in 2020 and 2050. External costs of GHG emissions for motor vehicles will be assessed by applying the life cycle assessment of GHG emissions from vehicles and integrating price of carbon obtained by 10 climate change mitigation policy scenarios run using various energy models.

2. Comparative assessment of motor vehicles

The climate change mitigation policy oriented road transport technologies assessment will be performed for EU under 10 climate change mitigation scenarios in 2020 and 2050 by integrating carbon price in calculating external costs of GHG emission for future motor vehicles. Further motor vehicles will be ranked in 2020 and 2050 under 10 climate change mitigation scenarios based on the total social costs (the sum of external costs of GHG emissions and private costs).The main indicators for motor vehicles comparative assessment applied in this paper are private (fuel and vehicle) costs and life cycle external costs of GHG emissions of motor vehicles. The life cycle GHG emissions indicator reflects the potential negative impacts of the global climate change caused by emissions of greenhouse gases for the ride of 1 vehicle km. It follows the methodology of IPCC [1,2] and covers complete energy carrier chains. Life cycle GHG emissions and related external costs of motor vehicles are the main indicators for environmental impact assessment of motor cars and serve as important policy guiding alert [3,4].

Further seeking to integrate long-term future road transport technology assessment and ranking with results of long-term climate change mitigation scenarios run the carbon price obtained by various climate change mitigation scenarios runs was applied in the calculation of the GHG emission externalities for the selected main future motor vehicles.

3. Carbon price development

Within EU FM 7 project Planes [5] aiming at assessment of future energy technologies the assessment of energy technologies was performed based on carbon price development. The climate change mitigation scenarios integrating various GHG emission reduction commitments and climate change mitigation targets can provide information on carbon price developments over time frame. The carbon price development in EU was obtained for 2020 and 2050 by running 10 climate change mitigation scenarios by energy models (ETSAP-TIAM, DEMETER, GEMINI and WITCH) [6].

10 policy scenarios runs were performed for 4 models (Table 1):

- First best scenarios: FB-3p2 and FB-3p5 setting alternative targets after 2050: 3.2 W/m^2 and 3.5 W/m^2.
- Second best policy scenarios:
  1. SC1-3p2 – to reach commitments indicated in Table 1 for SC1 linearly declining from business as usual from start date (Table 1) to the indicated of 2005 emissions. The target after 2050: 3.2 W/m^2
  2. SC1-3p5 – to reach commitments indicated in Table 1 for SC1 linearly declining from business as usual from start date (Table 1) to the indicated of 2005 emissions. The target after 2050: 3.5 W/m^2
  3. SC2-3p2 – to reach commitments indicated in Table 1 for SC2 linearly declining from business as usual from start date (Table 1) to the indicated of 2005 emissions. The target after 2050: 3.2 W/m^2
  4. SC2-3p5 – to reach commitments indicated in Table 1 for SC2 linearly declining from business as usual from start date (Table 1) to the indicated of 2005 emissions. The target after 2050: 3.5 W/m^2.

Table 2
GHG price in EU in 2020 and 2050 EUR (2005)/metric tonnes of CO_2 eq.

	2020	2050
REF	0	0
FB-3p2 scenario	21–48	195–573
FB-3p5 scenario	13–48	195–297
SC1-3p2 scenario	3–21	107–248
SC1-3p5 scenario	3–13	110–289
SC2-3p2 scenario	3–14	110–229
SC2-3p5 scenario	3–13	110–268
VAR1-3p2scenario	0–14	113–192
VAR1-3p5 scenario	3–14	114–238
VAR2-3p2 scenario	0–15	115–164
VAR2-3p5 scenario	3–15	114–203

The set of 4 variant second best policy scenarios are the same as for four second best scenarios, but with a limitation on the purchasing of carbon permits between 2020 and 2050, during which period at least 80% of abatement (defined as business usual minus the allocation) has be undertaken domestically by each region, and at most 20% of the abatement can be done with international offsets (purchase of permits). The trade restriction is levied from 2050 onwards [7].

The range of carbon price in 2020 and 2050 for EU obtained by 10 climate change mitigation policy scenario runs for ETSAP-TIAM, DEMETER, GEMINI and WITCH models are presented in Table 2 [7].

The following 10 road transport technologies were selected for assessment: hybrid electric sedan-type vehicle (HEV); three plug in hybrid vehicles (PHEV) powered with petrol and electricity from grid; conventional sedan type vehicles using petrol and diesel and vehicles using bioethanol from sugar beet, bioethanol from wheat and biodiesel from rapeseed and biodiesel from vegetable oil. The PHEVs considered have electric ranges of 30 km (PHEV30), 60 km (PHEV60) and 90 km (PHEV90) [8,9]. A HEV can use on-board battery to travel on electricity from grid and it can operate as traditional HEV, burning liquid fuels. PHEVs provide electric powered travel using battery which can be recharged at electric outlets, hence PHEVS substitute electricity for petrol to supply a portion of the power needed for travel. The different electric ranges depend on the battery and other characteristics of the vehicle [10–13].

In the following chapters of paper based on recent scientific literature review and results of various EU funded projects the range

Table 3
Life cycle GHG emissions of the main future motor vehicles.

	Range of CO_2 g/vehicle km	Average CO_2 g/vehicle km
HEV	180–192	186
PHEV 30	126–183	154
PHEV 60	104–181	143
PHEV 90	96–183	140
Petrol	227.4–307.6	268
Diesel	243.0–251.7	247
Bioethanol from sugar beet	103.5–120.2	112
Bioethanol from wheat	43.5–75.5	59.5
Biodiesel from rapeseed	109.1–120.2	115
Biodiesel from waste vegetable oil	30.8–41.9	36

of life cycle GHG emissions and private costs for the selected motor vehicles will be derived [14–19]. The average values of life cycle GHG emissions and private costs were further used for comparative motor vehicles assessment and ranking. The most competitive road transport technologies will be identified based on external costs of GHG emissions and total costs for the 10 climate change mitigation scenarios. Climate change mitigation policy oriented comparative assessment of motor vehicles can provide information on the most attractive future road transport technologies taking into account climate change mitigation targets and GHG emission reduction commitments set for world regions.

4. Life cycle GHG emissions and private costs of future motor vehicles

4.1. Life cycle GHG emissions of motor vehicles

The range of life cycle GHG emissions of transport technologies in g/vehicle km were obtained by gathering data on GHG emissions from transport sector from various sources [14–19] evaluating direct CO_2 emissions from combustion and total life cycle GHG emissions for specific motor vehicles. Fuel GHG intensity is the key factor which represents the net lifecycle emissions impact associated with the consumption of a unit of fuel. Sometimes termed a fuel's "carbon footprint", it can be expressed in units of grams of carbon dioxide-equivalent per megajoule (gCO_2 eq/MJ) of energy delivered to vehicles or other transportation equipment. Fuel GHG intensity is the main factor among many that contribute to transportation emissions. The rages of life cycle GHG emissions in g CO_2/vehicle km and average life cycle GHG emissions for various fuels and motor vehicles types are presented in Table 3.

The life cycle GHG emissions of PHEVs depend on the vehicle, battery and on the GHG intensity of the electricity and liquid fuel used to power the vehicle [8–13]. As GHG intensity of electricity used to charge PHEVs is the key parameter in estimating the life cycle GHG emissions the several scenarios ranging from average carbon intensity of electricity (670 g CO_2 eq/kWh) to low carbon intensity of electricity (200 g CO_2 eq/kWh) scenarios [17]. The low carbon scenario describes an energy system where renewables, nuclear or coal with carbon capture and sequestration, account for a large share of the generation, thus making the GHG intensity of electricity low. Taking into account EU climate change mitigation and energy policies such scenario is the most probable in 2020 and especially in 2050. The average intensity of the current EU power portfolio makes about 600 g CO_2/kWh.

The range of life cycle GHG emissions from biofuels and fossil fuels were obtained from generalizing results of various studies dealing with life cycle assessment biofuels [20–26].

As one can see from information provided in Table 3 biodiesel from waste vegetable oil has the lowest life cycle GHG emission followed by bioethanol from wheat. Petrol based transport technologies have the highest life cycle GHG emissions followed by diesel based transport technologies. Life cycle GHG emissions of hybrid and plug in hybrid vehicles are in between biofuels and conventional vehicles based on liquid fuels.

4.2. Private costs of motor vehicles

The range of current private costs of road transport technologies was evaluated in EURcnt/vehicle km based on information about costs of fuels and vehicles costs provided by various data sources [15–17,19] and are presented in Table 4. The total private costs expressed in vehicle km are obtained by summing up fuel costs per vehicle km, electricity costs per vehicle km for PHEV and vehicle costs per vehicle km assuming that useful life time of all vehicles is 240,000 km [8]. The price of petrol and diesel in 2020 is based on cost of crude oil c.$50/barrel (FOB Gulf cost). The fuel costs of HEV and PHEV in 2020 and 2050 are evaluated applying petrol and diesel prices and fuel efficiency assessments performed in studies [8,9,13]. The costs for biofuels vary widely depending on location for existing bioethanol and biodiesel technologies [21,22,24–28].

As one can see from information provided in Table 4 in 2020 the most expensive in terms of fuel costs are bioethanol and biodiesel based technologies and the cheapest are hybrid cars. The most expensive vehicles in terms of vehicles costs are plug in hybrid vehicles, especially PHEV 90. In terms of total private costs the cheapest road transport technologies are conventional technologies based on diesel followed by HEV. Therefore the transport technologies having the lowest life cycle GHG emission are among the most expensive terms of total private costs. Especially high are fuel costs for biofuels. As regards of vehicle costs the cheapest are conventional motor vehicles.

The long range fuel costs and vehicle costs were assessed in 2050 (Table 5) based on forecast of gasoline and diesel prices and by applying the same assumptions for evaluation of vehicle costs as in case of year 2020 [8].

As one see from Table 5 the motor vehicles using biofuels have the highest fuel and private costs in 2050. The hybrid cars and conventional vehicles have similar private costs in 2050 though conventional vehicles have the highest fuel costs in 2050. The high vehicle costs of hybrid car technologies in some cases (PHEV 90) overweigh fuel costs of conventional vehicle technologies.

Further policy oriented assessment of road transport technologies will be performed by applying carbon price obtained by 10 policy scenarios runs.

5. Ranking of future motor vehicles under various climate change mitigation constraints

Seeking to compare motor vehicles based on carbon price developments several most reliable scenarios were selected: first best and second best scenarios [7]. The average carbon price data for OECD region was further applied for the evaluation of external GHG emission costs. As the first best scenarios and second best scenarios include specific targets: 3.2 W/m^2 and 3.5 W/m^2 the scenarios with stricter target were used motor vehicles assessment and ranking.

Motor vehicles were compared based on external costs and total costs in 2020 and 2050 (Table 6). The same ranking of transport technologies based on external costs of GHG emissions was achieved for all policy scenarios considered and for both time frameworks: 2020 and 2050 as the same life cycle GHG emissions costs were applied. The most competitive transport technologies based on external GHG costs are technologies having the lowest life cycle GHG emissions, i.e., biodiesel from waste vegetable oil based technologies followed by bioethanol from wheat and from sugar beet based technologies.

Table 4
Private costs of motor vehicle in 2020, EURcnt/kWh.

	Average fuel costs			Average electricity cost			Average vehicle costs, EURcnt/km	Total average private costs, EURcnt/vehicle km
	EURcnt/ litre	Litres/ vehicle km	EURcnt/ vehicle km	EURcnt/ kWh	kWh/ vehicle km	EURcnt/ vehicle km		
HEV	50	0.057	2.85	–	–	–	9.0	11.9
PHEV 30	50	0.042	2.1	8	0.2	2.4	9.1	12.8
PHEV 60	50	0.03	1.5	8	0.25	3.0	9.9	13.4
PHEV 90	50	0.02	1.0	8	0.3	3.6	12.2	15.6
Petrol	50	0.08	4.0	–	–	–	7.2	11.2
Diesel	40	0.08	3.2	–	–	–	7.0	10.2
Bioethanol from sugar beet	70	0.08	5.6	–	–	–	7.2	12.8
Bioethanol from wheat	90	0.08	7.2	–	–	–	7.2	14.4
Biodiesel from rapeseed	60	0.08	4.8	–	–	–	7.0	11.8
Biodiesel from waste vegetable oil	80	0.08	6.4	–	–	–	7.0	13.4

Table 5
Private costs of motor vehicle in 2050, EURcnt/kWh.

	Average fuel costs			Average electricity cost			Average vehicle costs, EURcnt/km	Total average private costs, EURcnt/vehicle km
	EURcnt/ litre	Litres/ vehicle km	EURcnt/ vehicle km	EURcnt/ kWh	kWh/ vehicle km	EURcnt/		
HEV	120	0.057	6.84	–	–	–	9.0	15.8
PHEV 30	120	0.042	5.04	12	0.2	2.4	9.1	16.5
PHEV 60	120	0.03	3.6	12	0.25	3.0	9.9	16.5
PHEV 90	120	0.02	2.4	12	0.3	3.6	12.2	18.2
Petrol	120	0.08	9.6	–	–	–	7.2	16.8
Diesel	110	0.08	8.8	–	–	–	7.0	15.8
Bioethanol from sugar beet	160	0.08	12.8	–	–	–	7.2	20.0
Bioethanol from wheat	200	0.08	17.6	–	–	–	7.2	24.8
Biodiesel from rapeseed	146	0.08	11.7	–	–	–	7.0	18.7
Biodiesel from waste vegetable oil	180	0.08	14.4	–	–	–	7.0	21.4

As one can see from data provided in Table 6 the cheapest motor vehicles according the first best policy scenario in terms of total social costs in 2020 are conventional vehicles and the most expensive are PHEV 90 and bioethanol based road transport technologies. In 2050 according total social costs the most expensive are conventional vehicles as high external costs of GHG emissions in 2050 according strict first best policy scenario overweight the low private costs of these technologies. In 2050 the total social costs of hybrid motor vehicles are similar to biofuel based vehicles.

In Figs. 1 and 2 the total costs of motor vehicles are provided in 2020 and 2050 respectively according the first best scenario FB-3p2.

As one can see from Fig. 1 in 2020 it is obvious that petrol and diesel fuel based conventional motor vehicles are the most competitive as carbon price and external costs of GHG emissions do not overweight fuel price differences in transport technologies assessment. The most expensive technology is PHEV 90 followed by bioethanol from wheat and PHEV 60.

However as one can see from Fig. 2 the high carbon price in 2050 according first best policy scenario makes hybrid motor vehicles and motor vehicles based on biofuels more competitive than those of fossil fuel based. The ranking of motor vehicles based on total social costs according the first best policy scenario in 2020 and 2050 provides opposite results. Because of the high carbon price in 2050 the petrol and diesel based transport technologies are ranked as the least attractive in this year though in 2020 these transport technologies are ranked as the most competitive. The cheapest technologies in 2020 are PHEV 60 and PHEV 30 followed by biodiesel from waste vegetable oil technology which has the lowest external GHG emission costs.

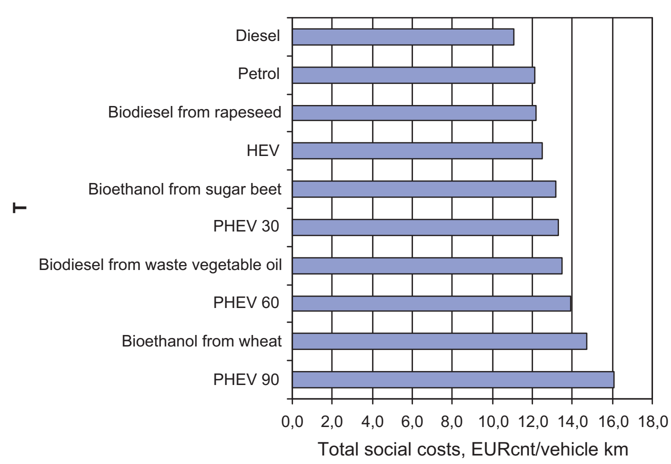

Fig. 1. The average social (private and external costs of GHG emissions) costs of road transport technologies in 2020 according the more strict first best policy scenario FB-3p2.

Further motor vehicles are ranked based on total social costs according strict second best policy scenario SC1-3p2. In Figs. 3 and 4 the average total social costs of motor vehicles are provided in 2020 and 2050 respectively according the second best policy scenario SC1-3p2.

As one can see from Fig. 3 the most competitive motor vehicles according the second best policy scenario like in the case of the first best scenario in 2020 are conventional vehicles based on fossil fuels. The ranking of motor vehicles in 2020 according the first

Table 6
Long-term private and external costs of motor vehicle according first best policy scenario FB-3p2 in 2020 and 2050, EURcnt/kWh.

	2020				2050	
	Average private costs, EURcnt/vehicle km	Average external costs of GHG emissions, EURcnt/vehicle km	Total average social costs, EURcnt/vehicle km	Average private costs, EURcnt/vehicle km	Average external costs of GHG emissions, EURcnt/vehicle km	Total average social costs, EURcnt/vehicle km
HEV	11.9	0.6	12.5	15.8	7.1	22.9
PHEV 30	12.8	0.5	13.3	16.5	5.9	22.4
PHEV 60	13.4	0.5	13.9	16.5	5.5	22.0
PHEV 90	15.6	0.5	16.1	18.2	5.4	23.6
Petrol	11.2	0.9	12.1	16.8	10.3	27.1
Diesel	10.2	0.9	11.1	15.8	9.5	25.3
Bioethanol from sugar beet	12.8	0.4	13.2	20.0	4.3	24.3
Bioethanol from wheat	14.4	0.2	14.7	22.8	2.3	25.1
Biodiesel from rapeseed	11.8	0.4	12.2	18.7	4.4	23.1
Biodiesel from waste vegetable oil	13.4	0.1	13.5	21.4	1.4	22.8

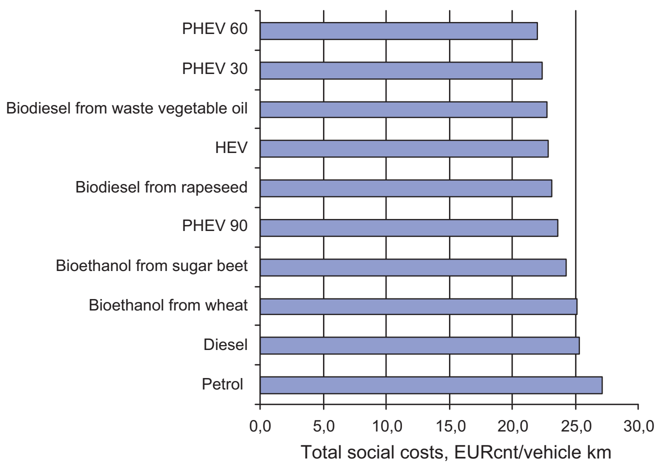

Fig. 2. The average social (private and external costs of GHG emissions) costs of road transport technologies in 2050 according the more strict first best policy scenario FB-3p2.

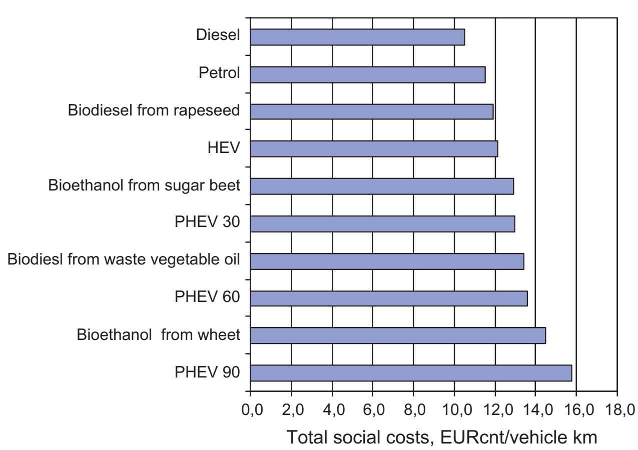

Fig. 3. The average social costs of road transport technologies in 2020 according the second best scenario SC1-3p2.

best and second best policy scenarios provides the same results for all technologies because of very low carbon price (3–21 EUR/t CO_2 in SC1-3p2) and (21–48 EURcnt/tCO_2 in FB-3p2) which do not have significant impact on technologies ranking as private costs are significantly higher and considerably overweight external GHG emission costs in total social costs assessment.

As one can see from Fig. 4 according the second best scenario in 2050 the most expensive road transport technologies

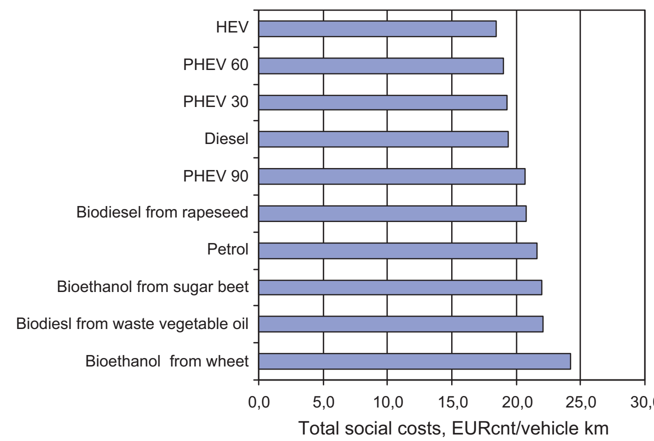

Fig. 4. The average social costs of road transport technologies in 2050 according the second best scenario SC1-3p2.

are based on biofuels. As the second best policy scenarios have almost twice lower carbon prices (178 EUR/tCO_2 eq and 170 EUR/tCO_2 eq) in 2050 comparing with the first best policy scenario (375 EUR/tCO_2 eq) it provides very different ranking of motor vehicles comparing with the first best policy scenario. Though in 2020 the most competitive road transport technologies are those based on petrol and diesel like in the case of the first best policy scenario however the least attractive motor vehicles according the second best scenario are technologies based on bioethanol from wheat and biodiesel from waste vegetable oil. This is related with the fact that carbon prices obtained during the second best policy scenarios runs in all time frame are too low to overweight the high fuel costs of biofuels.

6. Conclusions

The long-term assessment of new energy technologies in road transport sector was performed in the paper for various long-run climate change mitigation policy scenarios in European Union taking into account 2 main criteria: private costs (fuel and vehicle costs) and external GHG emission costs. Such policy oriented road transport technologies assessment based on carbon price and private costs of transport technologies can provide information on the most attractive future motor vehicles taking into account climate change mitigation targets and GHG emission reduction commitments for world regions.

The ranking of motor vehicles based on total social costs obtained for specific policy scenarios and time frames highly depends on carbon price implied by specific climate change mit-

igation scenarios. Very high carbon prices make more competitive technologies having low life cycle GHG emission such as based on biofuels or plug in hybrid vehicles though these technologies in terms of fuel and vehicle costs are more expensive than other technologies but external costs of GHG emissions in high carbon price scenarios in 2050 usually overweight the private costs in technologies ranking.

Because of very high carbon prices in 2050 in the first best policy scenario FB-3p2 the carbon price is the main determinant in road transport technologies ranking and there are no big differences in transport technologies ranking in this year for all policy scenarios. Motor vehicles having low life cycle GHG emissions are the most competitive. Especially the first best policy scenario provides for the competitive advantage of low carbon road transport technologies such as biodiesel and bioethanol.

The most competitive motor vehicles according the first best and second best policy scenarios in terms of total social costs in 2020 are conventional technologies and the most expensive are PHEV 90 and bioethanol based road transport technologies. According the first best policy scenario in 2050 the most expensive road transport technologies are conventional vehicles as high external costs of GHG emissions in 2050 according the first best policy scenario overweight the low private costs of these road transport technologies. In 2050 the total social costs of hybrid transport technologies are similar to biofuel based motor vehicles. According the second best policy scenario in 2050 the most competitive technologies are plug in hybrid cars and vehicles using biodiesel. The most expensive road transport technologies are bioethanol and biodiesel vehicles as too low CO_2 price according the second best policy scenario does not have positive impact on these transport competitive advantage.

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